INSIDE DIAMETER MEASUREMENTS FOR THE CYLINDER OF A 20 L PISTON PROVER

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Abstract: We made inside diameter measurements of a stainless steel cylinder used in a piston prover for hydrocarbon liquid flow measurements. We used a 3-point micrometer and two traceable setting rings to measure diameter at 12 radial positions at each of 21 lengthwise positions, on three different occasions. The diameter measurements showed a change in diameter (taper) of about 20 μm near the middle of the cylinder and non-circularity at one end. These shape imperfections lead to a diameter uncertainty of 6 μm (k=2) for the cylinder in its present form. This amounts to 75 parts in 10^6 uncertainty in the cross sectional area or flow measurements. The cylinder will be re-honed to improve the uniformity of diameter along the length and chrome plated to increase the surface hardness (to prevent scratches). Based on the measurements presented herein, diameter uncertainty of 2 μm or less appears attainable by this measurement approach (26 parts in 10^6 for flow).

1. INTRODUCTION

The NIST Fluid Metrology Group is replacing a dynamic gravimetric flow standard for hydrocarbon liquid flow measurement with piston prover flow standards. The smallest of the piston provers, the 2 L Hydrocarbon Liquid Flow Standard (HLFS) was commissioned in 2005 and covers flows from 0.2 L/min to 6 L/min with uncertainty of 0.01 % (k=2) [1, 2]. A prover with cylinder volume of 20 L is under construction now and is expected to cover flows up to 60 L/min or higher.

The HLFS piston prover uses an o-ring sealed piston inside a circular cylinder to measure flow. The piston (and hence the flow) is driven by a lead screw and a speed controlled motor. A system of piping and valves puts the flow through a section of straight pipe to calibrate a meter under test. The displacement of the piston is measured with a linear encoder that delivers 50 square wave pulses for each mm traveled. Once the piston reaches a steady state velocity (and steady state flow), the number of encoder pulses counted over a measured time interval is used to calculate flow. The liquid flow can be calculated by multiplying the piston velocity by the cross sectional area of the cylinder (and making corrections for thermal expansion effects in the liquid and prover materials). Equivalently, each encoder pulse can be considered to represent an element of volume of liquid displaced in the prover. Flow signals from the meter under test are averaged over the same time interval as the acquisition of piston prover flow data. For the 2 L flow standard, the cylinder volume was one of the two most significant uncertainty sources (31 %). The most significant uncertainty component was that of the liquid temperature difference between the cylinder and the meter under test (68 %) [1].

The piston prover can be operated in two modes: 1) with fixed start and stop positions at lengthwise positions of approximately 80 mm and 1080 mm from the end of the cylinder and 2) with start and stop positions at arbitrary locations between 80 mm and 1080 mm. Hence we will discuss 1) the uncertainty of the average diameter as well as 2) the difference between the average diameter and the diameter at any lengthwise position. In this particular system, the average diameter is used for both of these measurement modes and therefore, the difference between the diameter at any lengthwise position and the average diameter is the operative quantity for the uncertainty of the second mode.

Two methods for measuring the volume per encoder pulse are commonly employed. In a “water draw”, piping is temporarily connected to the piston prover so that all of the liquid displaced by the piston can be caught in a collection tank. The amount of liquid in the collection tank is measured gravimetrically or volumetrically while the piston is moved a measured number of encoder pulses. Care must be taken that gas bubbles are not present in the system and

Fig. 1 The 3-point micrometer and two setting rings used for diameter measurements of the piston prover cylinder.

several temperature corrections are necessary [3]. The second method (followed herein) uses dimensional measurements of the inside diameter of the cylinder.

The cylinder for the 20 L standard was salvaged from a piston prover originally constructed in 1991. It is made of stainless steel, has an inside diameter of 152.381 mm and is approximately 1 m long.

2. THE MEASUREMENT PROCESS

We selected a 3-point micrometer to measure the inside diameter of the cylinder because it is inexpensive, robust, and was expected to fulfill the uncertainty goals of our application. The micrometer was a Mitutoyo IT-005D* with range from 127 mm to 152.4 mm and resolution of 0.001 mm. We used two setting rings with diameters of 152.398 mm and 149.998 mm at 20 °C both with thermal expansion coefficients of 1.19×10^{-5} / °C. The micrometer has a ratchet stop to set the gaging force and it was equipped with an interface to transmit measurements directly to a computer spreadsheet when triggered by the operator.

Each day before making measurements with the micrometer in the cylinder, the micrometer scale was calibrated with the setting rings. First it was placed in the 152.398 mm ring and zeroed (because the diameter of the cylinder is closer to this setting ring). Then it was placed inside the 149.998 mm ring and the reading was recorded. Ten measurements were made with the micrometer inside each setting ring. The ratio of the temperature compensated setting ring dimensions and the micrometer measurements was used to obtain a gain value used to correct the cylinder measurements made with the micrometer for that day. The gain values were 0.999892, 0.999846, and 0.999809 on the three days of testing. Since the range of micrometer reading during the cylinder diameter measurements was < 25 μm, the largest calibration corrections applied to the micrometer readings were < 5×10^{-3} μm. However, departures from roundness by the setting rings can lead to micrometer calibration errors and we will assume a standard uncertainty of 0.5 μm for the uncertainty in the calibration of the micrometer.

* Certain commercial equipment, instruments, or materials are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by NIST, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

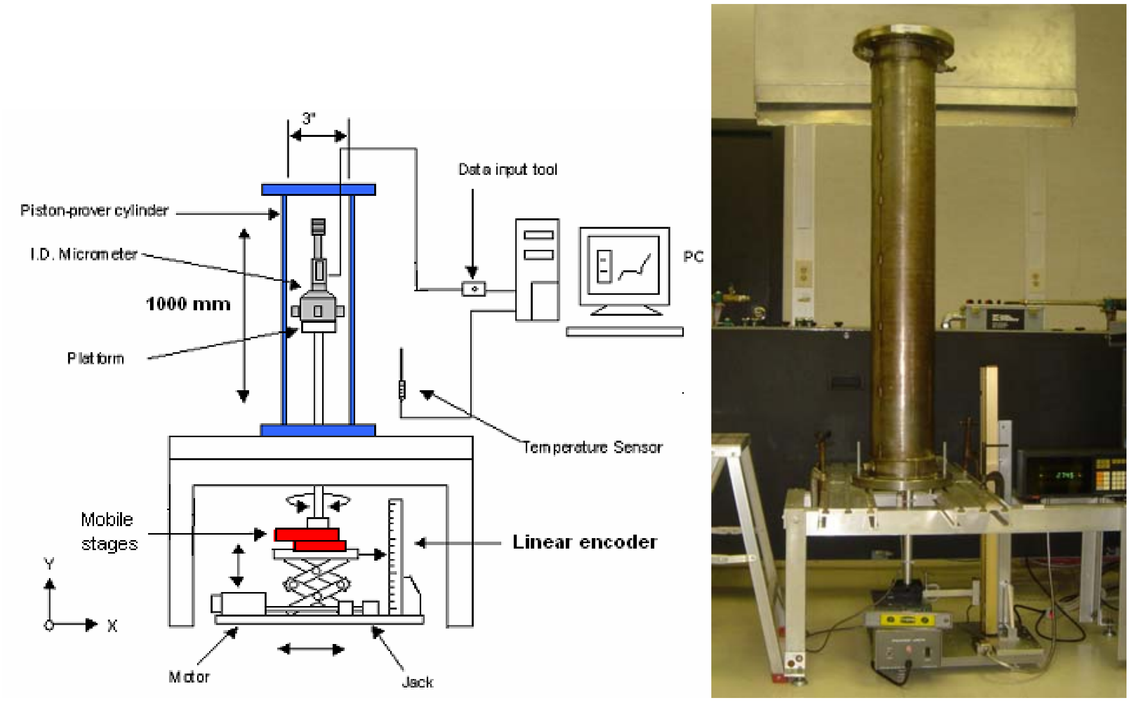

Fig. 2 Apparatus used to position the micrometer along the length of the cylinder.

A motorized lifting jack equipped with a linear encoder (I µm resolution) was used to raise the micrometer to each desired lengthwise position inside the cylinder (see Fig. 2). A two-axis stage was used to approximately center the micrometer in the cylinder. The micrometer was loosely held by a cradle so that as the micrometer was expanded to touch the walls, it could move freely and self center as designed by the manufacturer. Rods of various, known lengths were used to change the range of positions available from the motorized jack and cover half the cylinder length. The cylinder was flipped vertically and measured one half of its length at a time so that the operator could reach the micrometer to expand it against the cylinder walls. Overlapping measurements at the center of the cylinder were made in both orientations to check for consistency. A thermister was suspended close to the cylinder to make temperature measurements and allow us to calculate the cylinder diameter at a reference temperature of 20 °C.

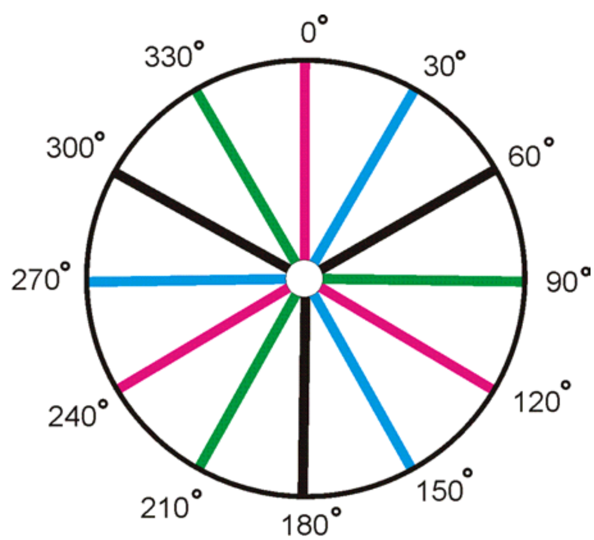

Fig. 3 Twelve angular positions of the micrometer at each lengthwise station resulted in different micrometer legs touching nominally the same points on the cylinder wall on three occasions.

At each lengthwise position, diameter measurements were made with the micrometer at 12 angular positions, 30 ° between each position. As illustrated in Fig. 3, the micrometer geometry leads to diameter measurements being made 3 times with the three micrometer legs on the same contact points of the cylinder surface, but with a different arrangement of the legs each time. The standard deviation of these 3 measurements was nearly always 2 μm or less and the differences can be attributed to small changes in the angular positioning, surface irregularities, tilting of the micrometer, errors in thermal expansion effects, etc.

3. RESULTS

Figure 4 shows the diameter, *D*, versus the lengthwise position, *x* for the 3 days of data collected. Each point is the average of the 12 measurements made at different angular positions with the micrometer. The dimensions have been corrected to a reference temperature of 20 °C using the thermal expansion coefficient (17×10^{-6} / °C) and the temperature measured during the test. The error bars represent the standard deviation of the 12 measurements made at each *x* position. The day to day agreement of the diameter measurements is 2 μm or less. The largest disagreement in the *D* measurements at the middle, *x* = 590 mm (where measurements were made on 6 different occasions) was 3 μm.

We found a steep change in the diameter of about 20 μm near the middle of the cylinder, presumably because the tube was honed one half at a time. The cylinder half covering *x* positions from 610 mm to 1100 mm is more consistent in diameter than the other half of the tube: its diameter is uniform within 5 μm. The other half of the cylinder is flared near the end and the diameter increases about 12 μm over 260 mm of its length.

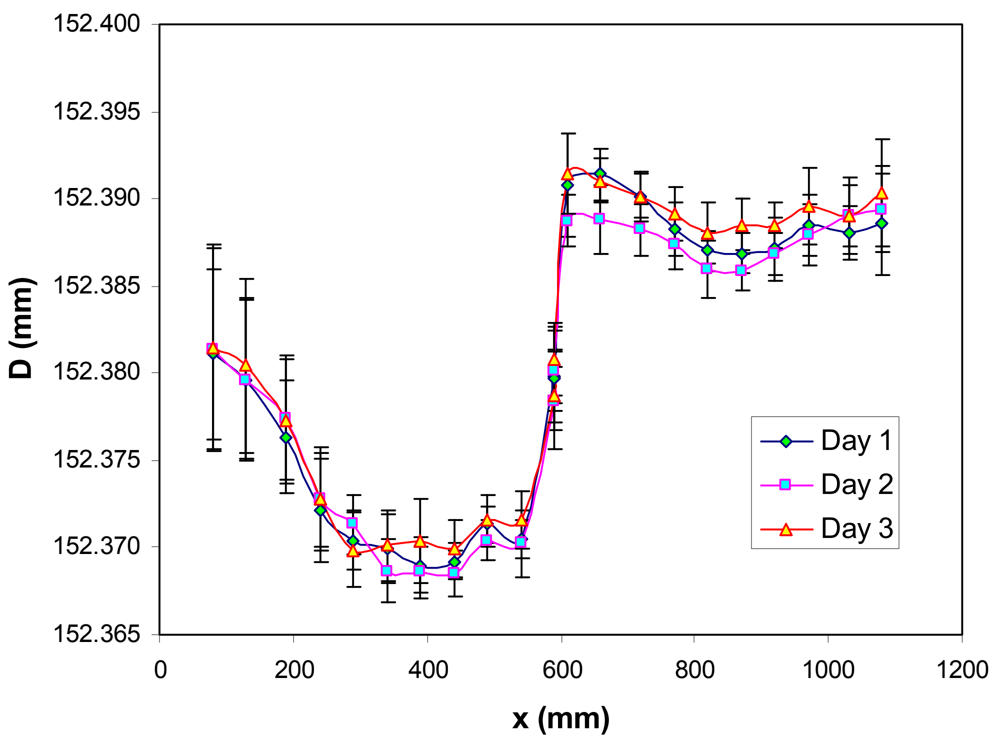

Fig. 4 Diameter measurements versus lengthwise position in the cylinder. Each point is the average of the 12 measurements made at different angular positions with the micrometer.

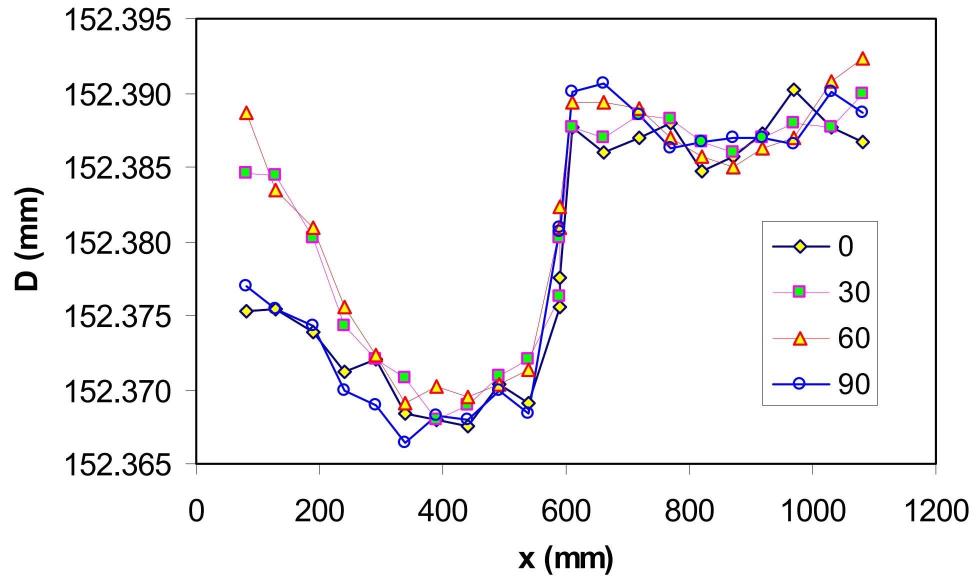

Fig. 5 Averages of diameter data at four angular positions (day 2 data only). Separation of curves at x < 300 mm shows that the cylinder is out of round at one end.

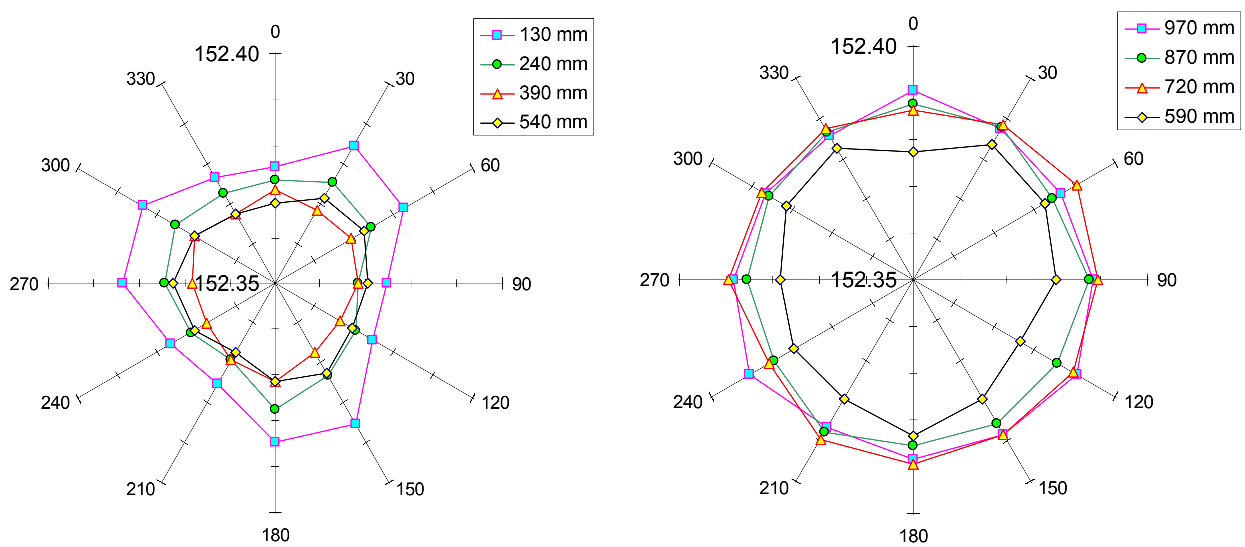

Fig. 6 Plots of the cylinder diameter at 8 of the 22 lengthwise positions for 12 angular positions of the micrometer (day 2 data only). Radial axes range from 152.350 mm (center) to 152.400 mm and they are labeled with their angle in degrees.

In Fig. 5 we plot the average of the three measurements made with the micrometer legs touching the same locations (but with different legs) on the cylinder wall (day 2 data only). The four curves are for data collected when one of the micrometer legs was located at the four angles of 0°, 30°, 60°, or 90°. Figure 5, along with Fig. 6 allows one to examine the roundness of the cylinder at various lengthwise positions. Figure 5 and Fig 6a show that for positions less than 300 mm, the diameter measurements for micrometer positions of 30° and 60° begin to grow larger than for the other two angles as x decreases, showing that the cylinder is not circular at this end. In Fig. 6b, we can see that the cylinder is rounder and more uniform in diameter at $x > 600$ mm.

3.1 Uncertainty Analysis

We averaged the 792 (3 x 12 x 22) individual diameter measurements to calculate the cylinder diameter for lengthwise positions between 80 mm and 1080 mm. The uncertainty of the average diameter is the quadrature sum of individual uncertainty components. These components are categorized as type A and type B [4, 5, 6]. The uncertainty components, along with an explanation of how they were estimated, whether they are type A or B, and their *k*=1 or standard uncertainty values, are given below.

a) Diameter of the setting rings: The standard uncertainty of setting ring calibrations by the NIST Precision Engineering Division is < 0.1 μm. Imperfect setting ring roundness leads to a standard uncertainty due to the setting ring of 0.5 μm (type B).
b) Micrometer linearity and resolution: The linearity uncertainty is negligible because the cylinder diameter is so close to the diameter of one setting ring (< 30 μm). Elastic deformation of the cylinder and micrometer are negligible. Standard uncertainty due to resolution is 1/2 the resolution 1 μm or 0.5 μm (type B).
c) Thermal expansion corrections: Temperature changes during the measurements were always < 0.4 °C. The standard uncertainty due to differential thermal expansion effects between the micrometer and the cylinder is 0.2 μm (type B). Thermometer calibration uncertainties are negligible (< 0.01 °C).
d) Imperfections in the cylinder shape (form errors) [7]: Based on our analysis of plots like Figs. 5 and 6 and the imperfect ability of the 3-point micrometer to identify elliptical or lobed shapes, we estimate the standard uncertainty due to geometric imperfections to be 2 μm (type B).
e) Repeatability and reproducibility of the diameter measurements: Gage alignment and cosine errors are represented in the repeatability. For the uncertainty of the average diameter over the entire measured length, we use the standard deviation of the mean, 2 μm (type A).

From these components we calculated a combined uncertainty of 2.9 μm and an expanded (k=2) uncertainty of 5.8 μm (38 parts in 10^6) for the average diameter, 152.381 mm at 20 °C.

It should be noted that the diameter at certain locations in the cylinder differs from the average diameter by 12 μm. If the piston were used over an inopportune portion of its stroke and the average diameter were used to calculate the volume of fluid displaced, errors as large as 79 parts in 10^6 can result, twice as large as the uncertainty given above.

For the portion of the cylinder between $x = 610$ mm and 1080 mm, the repeatability and circularity are dramatically better than for the cylinder taken as a whole. For this portion of the cylinder, the uncertainties given in categories d) and e) above drop to 1 μm and 0.3 μm respectively and the expanded uncertainty for the average diameter of this portion of the cylinder is only 1.3 μm or 8 parts in 10^6.

4. DISCUSSION AND CONCLUSIONS

We made 792 measurements of the inside diameter of a hydrocarbon liquid piston prover cylinder with a 3-point micrometer. Our measurements indicate that the cylinder was machined in two sections: there is a change in diameter of about 20 μm near the middle of the cylinder. Also, the cylinder is out of round and flared at one end.

Using dimensional metrology to determine the volume per encoder pulse has the advantage over the water draw method that one can detect sudden changes in diameter with respect to length and out of round shapes that increase the likelihood of rapid wear of piston seals or leaks past the seals. Ideally, both dimensional metrology and the water draw method should be performed to check for consistency of results between the two methods.

The average diameter over the measured length of this cylinder was 152.381 mm and the uncertainty of the average diameter was 5.8 μm (38 parts in 10^6). The largest difference between the average diameter and the diameter at any particular position was 12 μm (79 parts in 10^6).

Data for the better half of the cylinder shows that diameter uniformity < 5 μm is feasible. Our average diameter uncertainty for this portion of the cylinder is 1.3 μm or 8 parts in 10^6. If the full length of the cylinder were of this quality, the flow uncertainties resulting from using an arbitrary portion of the length would be about 13 parts in 10^6, i.e. six times better than now. Therefore, the cylinder will be re-honed to improve the uniformity of diameter along the length and chrome plated to increase the surface hardness (to prevent scratches). After re-work we will re-measure the inside diameter. Coordinate measuring machine profiles of the cylinder shape near the ends will be used to obtain better estimates of the uncertainty due to form errors.

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